DE89 011580

CONF-890403--11

LOW-ASPECT-RATIO OPTIMIZATION STUDIES FOR ATF-II[*]

S.P. HIRSHMAN, R.N. MORRIS[**], C.L. HEDRICK, J.F. LYON,
J.A. ROME, S.L. PAINTER, W.I. VAN RIJ[**]
Oak Ridge National Laboratory, Oak Ridge, Tennesee, United States of America

ABSTRACT. *A numerical procedure for optimizing stellarator MHD and transport properties at finite β is described. This method is applied to finding a low-aspect-ratio ATF-II configuration.*

Prompted by the economic and experimental attractiveness of low-aspect-ratio stellarators, we have initiated a study to optimize the plasma physics properties of such configurations. The design goal of this study is to decrease the aspect ratio, $A = R/a$, by a factor of two from $A = 7.8$ for the present ATF device to $A < 4$, without sacrificing MHD and transport performance. Stability to Mercier modes for $\langle\beta\rangle$ values up to 5% is considered essential for an attractive design. Also, a significant fraction of high-energy particles must be confined so that neutral-beam heating will be feasible in the next-generation experiments.

Previous studies at ORNL of the Compact Torsatron Sequence (CTS) [1] emphasized optimization of MHD high-β performance at low aspect ratios. Ancillary transport optimizations were performed by applications of vertical and quadrupolar magnetic fields. In spite of this, the particle confinement properties of these configurations deteriorated rapidly with increasing beta. In fact, for $\langle\beta\rangle > 2\%$, essentially all fast trapped alphas were lost in several poloidal transits. It seemed desirable to relinquish some of the stability margin afforded by the magnetic well in these configurations in order to improve their confinement properties. This observation then formed the impetus for the current study.

In order to extend the CTS studies into a regime of improved transport, it was necessary to broaden the range of allowable configurations. The CTS was restricted to stellarators produced by a single set of modulated current windings on a (prescribed) surface. By adopting an optimization approach that works directly with the shape of the outer plasma flux surface, we can avoid any *a priori* restrictions on the type of coils needed to produce a given magnetic configuration. In this way, the task of optimizing the physics properties of the stellarator is separated from the coil determination process. This division has the advantage that optimization of both MHD and transport can be performed simultaneously. However, unlike the CTS study, in the present method there is no guarantee that an acceptable coil set (from an engineering point of view) will result from the

---

[*] Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

[**] Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc., Oak Ridge, TN 37831, U.S.A.

physics optimization. The NESCOIL code [2] can be used, together with a judicious estimate for the coil winding surface(s), to yield a set of helical and/or modular coils with appropriate accessibility and dimensions.

The method described here is therefore similar to the optimization approach used in designing Helias [3], although it is being applied to a distinctly different set of physical criteria. In addition to being a low-aspect-ratio device (compared with A = 10 for Helias), the ATF-II design retains the basic rotational transform profile of ATF, i.e. strong shear in the outer plasma volume to provide interchange stability. Furthermore, whereas Helias has been optimized to reduce Pfirsch-Schlüter currents, the ATF-II design relies on the finite-β Shafranov shift arising from these currents to dig a well and hence improve its high-β stability. Finally, the ATF-II design does not attempt to generate a quasi-helical $|B|$ configuration, but rather uses the alignment of the B_{min} contours with the flux surfaces (see below) as a measure of the effective alpha-particle confinement. In this way, we can achieve factors of two to five improvement in confinement. This limited transport optimization is of practical significance, since it is probably not necessary to improve the neoclassical confinement beyond the point where it no longer dominates the expected anomalous diffusion.

The present stellarator optimization procedure requires an initial guess for the boundary of the desired configuration. This guess is determined by the large-aspect-ratio ATF and by the requirement that A/M (aspect ratio per field period M, or coil pitch for a fixed winding law) be approximately constant to maintain the edge value of iota. The three-dimensional equilibrium code VMEC is then used to process this boundary information (which, together with the requirement for zero net toroidal current and the pressure profile, completely specifies the MHD equilibrium) and to compute the relevant physical parameters required for optimization. For example, the equilibrium solution yields values for the edge and central values of iota, the percentage of the plasma volume that is Mercier stable, and various measures of transport performance. These parameters are passed to a nonlinear Newton optimizer, and an updated guess for the boundary is obtained which is consistent with improving the various optimization criteria. This loop is continued until no further improvement is obtained.

Because this loop may be repeated many times (10 - 30 iterations is typical) before terminating, it is crucial that the analytic optimization criteria be relatively easy to evaluate. This is certainly the case for the Mercier criteria. In the case of transport, however, it is not feasible to perform time-consuming Monte-Carlo simulations for each intermediate configuration. Rather, we opt for an approximate figure of merit for transport, based on the confinement of deeply helically trapped orbits of energetic (collisionless) particles. From J* conservation, it can be shown that these particles follow contours of $B_{min}(\Phi,\theta)$ = const, where the minimization of B is done with respect to the toroidal angle ϕ in a single field period, keeping the poloidal angle θ and toroidal flux Φ fixed. This criterion is easily evaluated and yields two topological parameters which characterize the confinement of trapped alphas: (i) *d*, the fraction of plasma volume enclosed by a B_{min} contour not

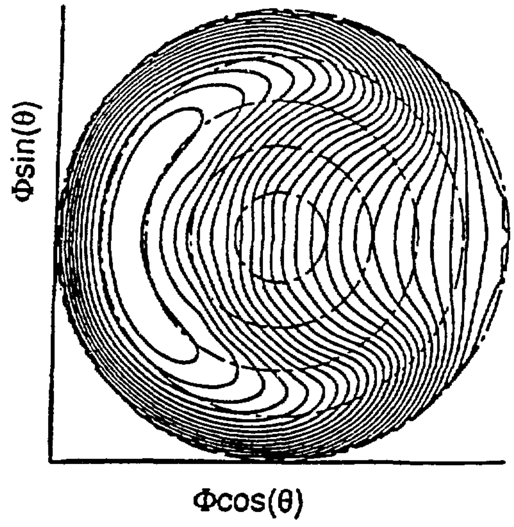

FIG. 1(a). B_{min} contours: no vertical field.

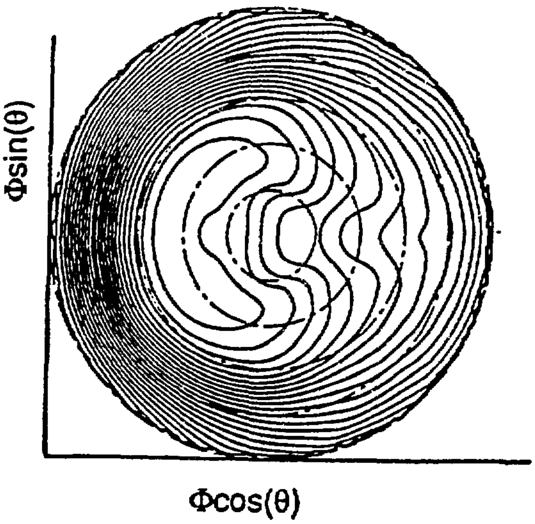

FIG. 1(b). B_{min} contours: vertical field applied.

intersecting the wall (d = 1 is desirable) and (ii) o, the offset of B_{min} with respect to the flux surfaces (o = 0 is desirable). Figure 1 illustrates the topological effects of these two parameters for an optimized ATF-II design at $\langle\beta\rangle = 2\%$. The concentric chain-dashed circles are the flux surfaces, and the solid curves are B_{min} contours. The application of a vertical field substantially improves trapped particle confinement in this case by both increasing d and simultaneously decreasing the offset parameter o. Indeed, this configuration, with the vertical field applied, has a trapped alpha loss fraction less than 10%. Of course, it is necessary to correlate these simplified confinement criteria with the actual confinement of a distribution (in pitch angle) of high-energy alphas, as calculated from a Monte-Carlo simulation. Figure 2 is a "bubble" plot of the fraction of confined alphas for various values of d and o. The biggest dots represent almost no loss, with the dot sizes being proportional to the confined fractions. (All the simulations of alpha particles presented here were performed with reactor scale parameters: B = 5T and $\bar{a}$ = 2m).

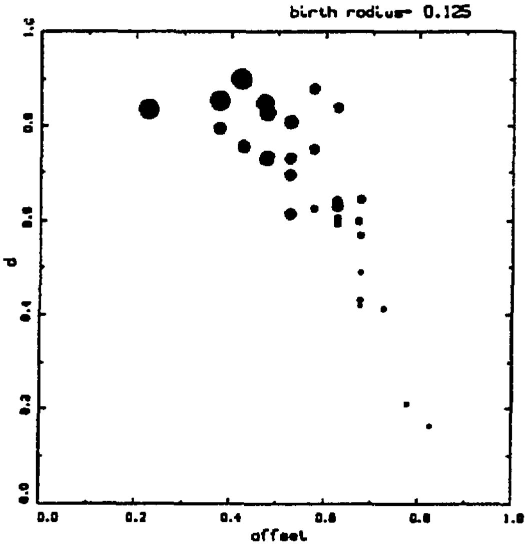

FIG. 2. Correlation of confined fast alphas with B_{min} parameters.

This figure shows that, in general, configurations with low values of offset ($o < 0.3$) and $d > 0.75$ also have good confinement properties.

Our numerical computations suggest that there is a relatively narrow range of boundary parameters at finite β that yield acceptable configurations. Therefore, configurations which are optimized at zero β generally do not make a good starting point for finding finite-β configurations. Rather, our design philosophy is to perform the optimization directly at finite β (*lowering* β is generally not a problem for maintaining good stability and transport properties). The only difficulty with this approach is that it is not possible to obtain the *exact* discrete coil set with NESCOIL, which requires a vacuum field. However, assuming that the main external contribution at finite β arising from the plasma currents is a vertical magnetic field, it is easy to obtain an *approximate* set of coils using NESCOIL. The vacuum magnetic surfaces obtained by such an optimization at $<\beta> = 2\%$ are shown in Fig. 3 for the two symmetry planes ($M\phi=0$ and $M\phi=\pi$, for $M=6$). Note that the plasma is centered at $R = 1.00$ (arbitrary units). Raising the $<\beta>$ to 2% yields the configuration shown in Fig. 4. Without a compensating vertical field (VF), the magnetic axis has shifted out to $R = 1.10$, while an applied VF recenters the configuration at $R = 1.00$. (The magnitude of the VF was determined to optimize the alignment of B_{min} contours and produced the results shown previously in Fig. 1.) Note that with the applied VF, the Shafranov shift is reduced. This produces an associated reduction of the magnetic well. Figure 5 shows the magnetic well with and without the VF coils. Not only is the well reduced in depth, but also its spatial extent is contracted from about $\Phi < 0.65$ with no VF to

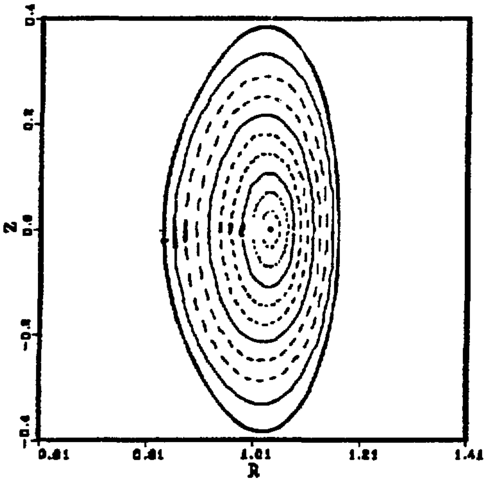

FIG. 3(a). Vacuum flux surfaces for ATF-II prototype, $M\phi=0$.

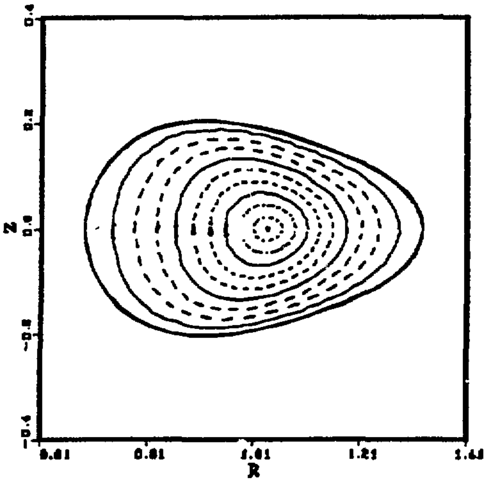

FIG. 3(b). Vacuum flux surfaces for ATF-II prototype, $M\phi=\pi$.

$\Phi < 0.45$ with an applied VF (Φ is the normalized toroidal flux). In spite of this erosion of the magnetic well, stability to Mercier modes is maintained throughout the discharge, as shown in Fig. 6. (For stability to Mercier modes, the curve marked *M* in Fig. 6 must be greater than zero.) The stabilizing contribution from the **J·B** term in the Mercier criterion (curve marked *C* in Fig. 6) increases and

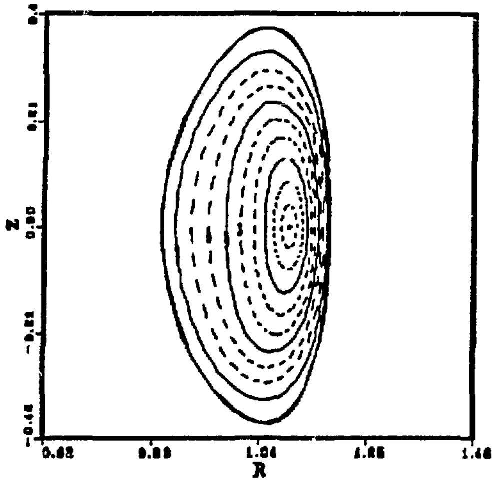

FIG. 4(a). <β> = 0.02, Mϕ=0.
No Vertical Field.

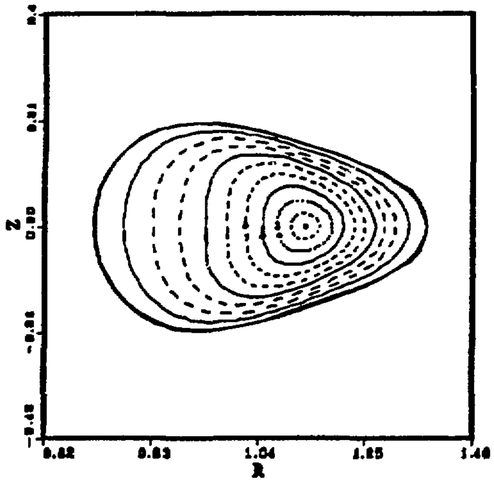

FIG. 4(b). <β> = 0.02, Mϕ=π.
No vertical field.

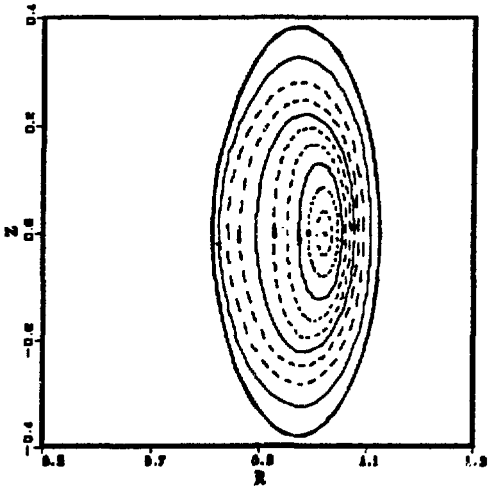

FIG. 4(c). With vertical field.

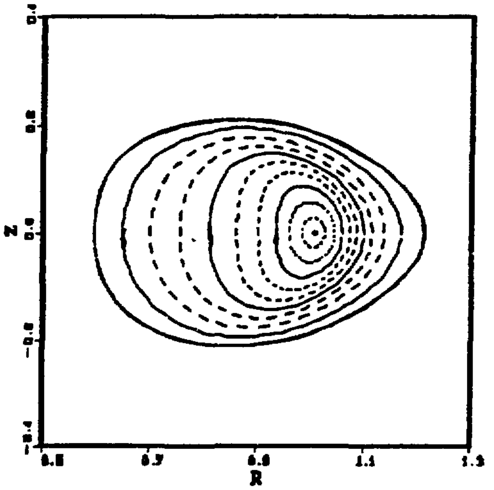

FIG. 4(d). With vertical field.

moves inward (toward smaller Φ) at the same rate as the well (curve *W*) disappears, so that global stability is maintained. In this sense, the stability of this configuration differs from the canonical ATF picture, which relies on a deepening, radially expanding well for high-β stability. Finally, the iota profile is nearly identical to the usual ATF result, with a small (15%) reduction (0.85 rather than 1.00) at the edge.

It should be noted from Fig. 4 that the effect of the VF coils is not confined to recentering the plasma, but also leads to a significant modification of the outer boundary shape. This change in the outer boundary has been accounted for self-consistently here by a free-boundary computation, and it can influence the confinement and stability properties of the plasma. Previous optimization methods assumed that the plasma boundary was fixed as $<\beta>$ increases, which is clearly not realistic with the addition of only VF coils.

Detailed coil design efforts using NESCOIL are reported in Ref. [4]. The optimized ATF-II configuration discussed here can be created using either modular or helical coils at a plasma-to-coil spacing of 15 cm (normalized to a major radius of 1 m). As this spacing is increased, the coils become increasingly kinked, and local areas of closed currents appear on the winding surface. Studies are under way to simplify these coils by removing selected helical or modular coil components and synthesizing the remaining currents on a different winding surface.

In conclusion, we have shown preliminary results which indicate that a low-aspect-ratio torsatron with adequate transport and MHD stability properties exists for $<\beta> < 2\%$. It remains a subject of continuing research to extend this

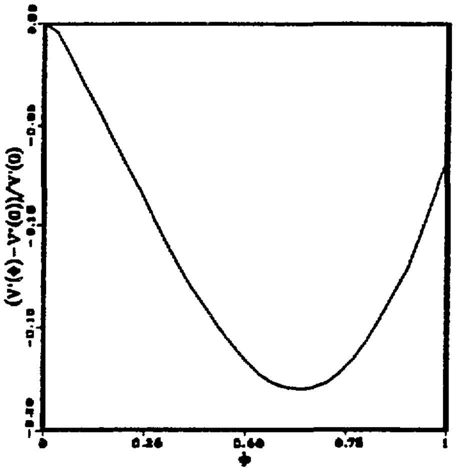

FIG. 5(a). Magnetic well.
No vertical field.

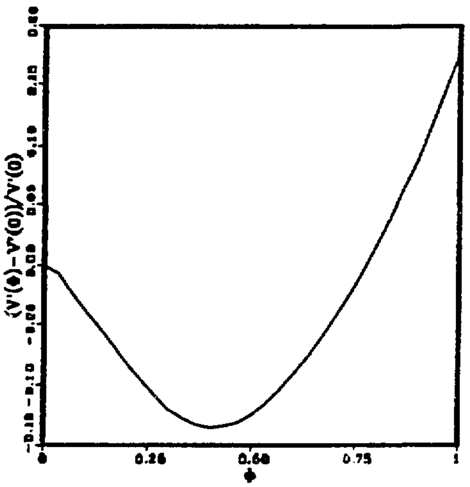

FIG. 5(b). Magnetic well.
With Applied vertical field.

configuration to a regime of increased <β>. The use of vertical fields to maintain high-energy particle confinement as <β> is raised has been demonstrated. Optimization of a finite-β plasma has been shown to be a robust way of accessing new and potentially attractive configurations. Although the exact determination of the vacuum coils is difficult, it is possible to obtain coils with sufficient accuracy so that the <β>-optimized parameters are not adversely affected.

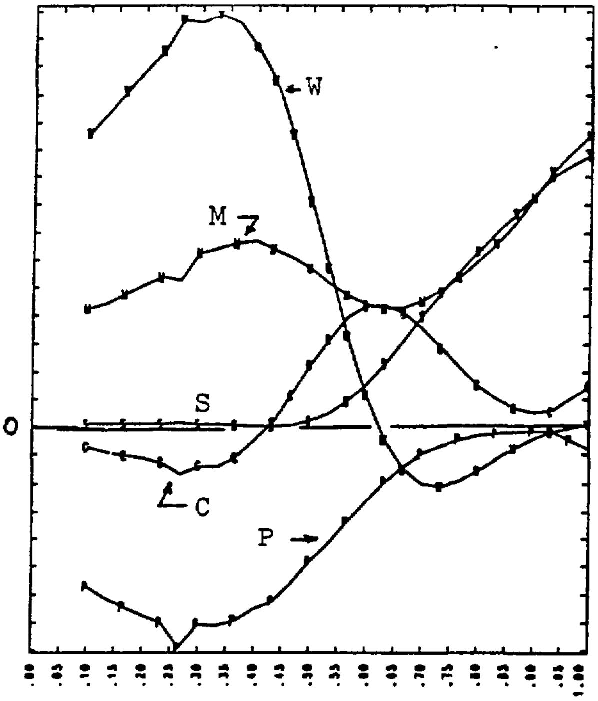

FIG. 6(a). Mercier stability criterion (M), no vertical field.

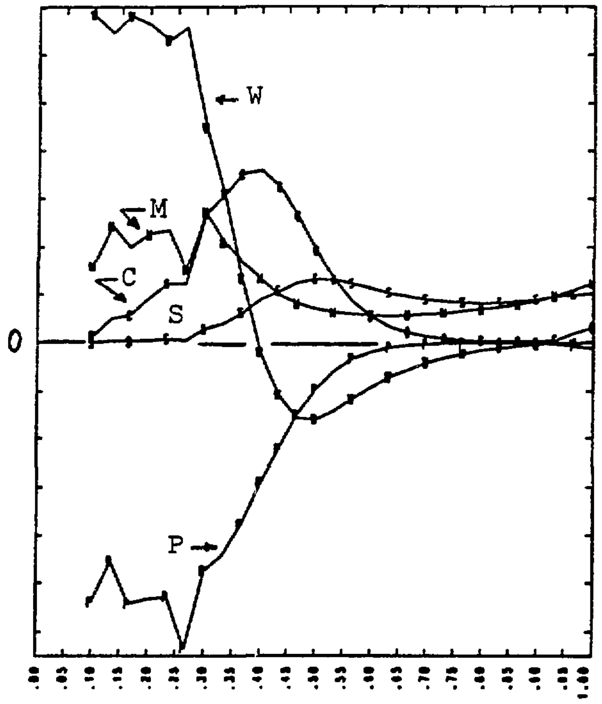

FIG. 6(b). Mercier stability criterion (M), vertical field applied.

REFERENCES

[1] CARRERAS, B.A., DOMINGUEZ, N., GARCIA, L., et al., Nucl. Fusion **28** (1988) 1195.
[2] MERKEL, P., Nucl. Fusion **27** (1987) 867.
[3] NÜHRENBERG, J., et al., these proceedings.
[4] ROME, J.A., et al., these proceedings.